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Pressure-driven capillary snap-off of gas bubbles at low wetting-liquid content

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Abstract

Snap-off is an important mechanism for generating discontinuous gas bubbles in porous media. Here, we use a hydrodynamic, corner-flow theory to re-examine the breakup of gas threads in constricted pores. Our primary focus is on the initial liquid volume within the corners of a pore and on the possibility of a minimum liquid content below which snap-off is inhibited. It is found that smoothly constricted pores with relatively small throats connected to large bodies exhibit excellent ability to snap-off regardless of their initial liquid content. Where such pores are present in porous media, it is predicted that strong foam is generated. Additional factors contributing to snap-off include elevated pressure gradients in the liquid phase and lamella or lens movement that establishes gradients in the axial profile of interfacial curvature. Our new results re-support successive snap-off as a viable mechanism of steady foam generation in homogeneous porous media at low overall aqueous-phase liquid content and at high liquid-phase pressure gradient.

Keywords: Snap-off; Strong foam generation; Pressure-driven flow; Corner flow

1. Introduction

During snap-off, liquid accumulates in the vicinity of pore throats due to gradients in the axial component of the curvature of the gas–liquid interface. If sufficient liquid builds, an unstable collar of liquid emerges, and the liquid spontaneously rearranges to a pore-spanning liquid lens, as illustrated in Fig. 1[1]. Later, this lens may be mobilized and/or drained of liquid to form a stable foam lamella, or vice versa, provided that surfactant is present. Thus, snap-off is divided logically into successive steps of liquid accumulation at pore throats, rearrangement of collars of wetting-liquid at throats into pore-spanning liquid lenses, and displacement of lenses or lamellae from pore throats. Snap-off repeats if ample wetting-liquid is available and the interfacial curvature at a pore throat is larger than the curvature in surrounding pore body(ies) [1].

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Nomenclature

List of symbols

Ca_m	modified capillary number
L	constriction wavelength (m)
p	phase pressure (Pa)
P_c	capillary pressure (Pa)
P_{cm}	minimum capillary pressure at any axial position during lens/lamella flow (Pa)
R	radius of largest inscribed circle in a pore cross-section (m)
z	axial distance along a constricted pore (m)

Greek letters

κ	dimensionless interfacial radius of curvature
λ	dimensionless pore radius
σ	surface tension (N m^{-1})
τ	dimensionless time
ζ	dimensionless axial distance

Subscripts and superscripts

$\sim$	dimensionless quantity
*	critical aspect ratio
c	Constriction
w	wetting phase

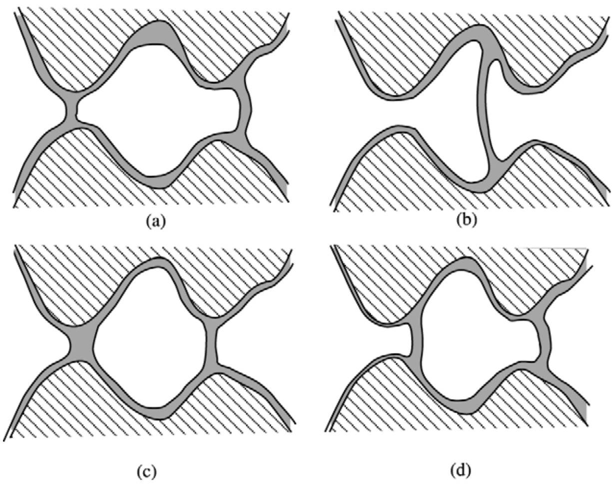

Fig. 1. Illustration of repetitive foam generation by snap-off: (a) a lamella preceding a large gas bubble (unshaded) enters the left-most pore constriction, (b) lamellae are displaced (flow is from left to right) from the pore-throat regions, (c) snap-off at pore throat (on left) and rearrangement of wetting-liquid into a pore-spanning lens, (d) displacement of lens/lamellae from the pore throat. After Ref. [1] by permission.

At the pore level, foam flow is a highly dynamic process, even at steady state. The rate of liquid flow through pore corners, or so-called ‘‘nooks and crannies’’, in the pore space of water-wet rock is crucial in the analysis of foam generation by snap-off. There is competition between the drainage time for lamella formation, the supply time for a collar to grow near a pore throat, and the time required to dislodge a lens or a foam lamella from a pore throat. On the other hand, the rearrangement of collars into pore-spanning lenses (Fig. 1 (c)) is essentially instantaneous relative to the time scales of the other two processes as shown both experimentally [2,3] and theoretically [4]. Thus, the rearrangement process is not rate determining and has an insignificant effect on the dynamics of snap-off. Where gas is immobile, obviously, generation of flowing foam is impossible. Nevertheless, the presence of immobile gas does not invalidate the snap-off mechanism because foam generation occurs only within the fraction of gas that is mobile. In general, analyses of foam generation in porous media must acknowledge the presence of pore corners, the resistance to flow within them, and the highly dynamic nature of foam flow.

Although there are other mechanisms and models for foam generation [5–9], the snap-off mechanism has been studied extensively. It is relevant to oil trapping, and snap-off is asserted as a dominant mechanism of foam generation in porous media [1–4,10–13]. Kovscek and Radke [1] developed a hydrodynamic theory to describe both pore-level liquid accumulation and lens displacement events in constricted, cornered pores. In this same work, a statistical network model is formulated to describe the porous-medium-averaged rate of foam generation by snap-off. It is shown that the generation rate is proportional to the product of the probabilities of liquid accumulation and lens/lamella mobilization. Hence, the bubble generation model of Kovscek and Radke [1] honors the fact that mobilization need not immediately follow liquid accumulation and that generation must cease if lenses or lamella cannot be mobilized. Application of the resulting foam generation rate [1] to predict actual foam displacement in porous media is quite successful [13–16].

Recently, however, Rossen [17] argues that the model for snap-off of Kovscek and Radke [1] is valid only upon initial displacement of a gas–liquid meniscus through a water-filled constricted pore. Once the downstream pores fill with gas bubbles, snap-off is purported to cease because enough liquid is not available and the curvature driving force for breakup is insufficient. Thus, Rossen concludes that “the mechanism of repeated snap-off as currently formulated and applied, cannot explain steady state foam generation in porous media” [17]. He discounts the possibility that snap-off arises through a combination of pore topology and gradients in interfacial curvature established by moving lenses or lamellae [17]. Rather, Rossen states that snap-off is governed by dynamic local fluctuations in capillary pressure arising, apparently, due to bubble movement [18]. For the interested reader, more extensive discussion of snap-off, and all foam generation mechanisms, are available elsewhere [12,13].

The objective of this paper is to extend our previous hydrodynamic theory [1] for snap-off of a gas thread in a smoothly constricted, cornered capillary to low corner-liquid contents. We are motivated by the earlier work of Chambers and Radke [12] who stated that snap-off during steady foam flow, at low wetting-liquid content, requires repeated, persistent flow of wetting-liquid into pores. Specifically, we document liquid accumulation at pore throats leading to snap-off in pores containing relatively little wetting-liquid, representative of that during steady foam flow in porous media. The conditions for the cessation of snap-off as media become dry are also elucidated. Importantly, the role of the pressure gradient along the wetting-liquid held in pore corners is highlighted. We also discuss the mechanisms by which local variations in capillary pressure arise and quantify pore-level snap-off dynamics.

2. Snap-off

In a medium where the gas saturation is relatively high, the question of snap-off is sensitive to the volume of liquid available in the vicinity of the pore, the imposed pressure gradient within the continuous wetting-phase, and the pore topology. Our previous work formulated the following evolution equation that describes the interplay of these factors [1]

$$\frac{\partial \kappa}{\partial \tau} = \kappa \frac{\partial^2 \kappa}{\partial \zeta^2} + 2\left(\frac{\partial \kappa}{\partial \zeta}\right)^2 - \mathrm{Ca_m}\kappa^2 \frac{\partial \kappa}{\partial \zeta}, \qquad (1)$$

where κ is the dimensionless interfacial radius of curvature normalized with respect to pore-body radius, ζ is the dimensionless axial coordinate normalized with respect to constriction wavelength, and τ is dimensionless time $(=t\sigma/(2\mu\beta R_b(L/R_b)^2))$. Within τ, σ is the interfacial tension, μ is the wetting-liquid viscosity, β describes the resistance to flow within the corner [19], R_b is the pore body radius, and L is distance between pore bodies in a serially constricted pore space. The term $\mathrm{Ca_m} = (4R_bL/\sigma)(-\partial p_w/\partial z)_{\mathrm{imposed}}$ is a modified capillary number that results naturally from net wetting-liquid flow along pore corners. Note that the term describing the net liquid flow grows in importance as the wetting-phase pressure gradient, and hence as Ca_m increases.

Eq. (1) neglects the curvature of the gas–liquid interface in the transverse (i.e. flow) direction compared to the interfacial curvature in the cross-section of the pore. This type of pore is described as “smoothly constricted” [2,20]. Ransohoff et al. [20] argue that a pore length to body size ratio (L/R_b) of order 10 or more is necessary to justify quantitatively this approximation. However, a careful re-examination of Eqs. (6)–(9) of [20] demonstrates that neglect of the transverse curvature introduces error of up to 1–15% in the static criterion for snap-off in square-shaped pores when $3 < L/R_b < 5$. The least error is associated with pores where the dimensionless constriction size (R_c/R_b) is small. These constricted pores are most likely to support snap-off, as proven shortly. Hence, we assert that Eq. (1) provides an approximate, but accurate, description of the corner drainage process for much smaller L/R_b ratios. Of course, porous media contain a variety of pore geometries. Some pores are classified as smoothly constricted and others as sharply constricted. In a sharply constricted pore, however, the transverse curvature can stabilize the interface prohibiting snap-off. The transverse curvature is opposite in sign to the cross-sectional curvature and prohibits snap-off whenever the transverse and cross-sectional curvatures are roughly equal. By way of verification, Legait [21] constructed sharp corners in a constricted square capillary and did not observe snap-off. Thus, smoothly constricted pores, and the behavior predicted by Eq. (1), are most relevant to snap-off in porous media.

For our calculations, we assume a dimensionless, serially constricted pore shape given by

$$\lambda(\zeta) = 1 - \frac{(1-\lambda_c)}{2}[1 + \cos(2\pi(\zeta_c - \zeta))], \quad (2)$$

where λ ($= R(z)/R_b$) is the local dimensionless axial size of the pore, $R(z)$ is the largest circle that may be inscribed locally in the pore cross-section, the subscript b denotes body, λ_c is the dimensionless constriction radius, and ζ_c describes the dimensionless position of the pore constriction. The cross-sectional shape of the pore is taken as square, but could in fact be any cornered polygon.

As Rossen correctly emphasizes [17], the initial profile of wetting-liquid in the corners is a critical parameter determining whether snap-off may occur in a constricted pore. Consider a lamella translating through the constricted cornered pore in 1 (a). We assume that the gas-phase pressure gradient is large enough to drive the lamella through both the first and second constrictions. If this is not the case, then blockage occurs, and, of course, such pores cannot be germination sites for further lamellae. As the lamella squeezes through the left constriction and emerges into the downstream body in Fig. 1 (b), wetting-liquid is deposited onto the pore wall and into the pore corners. The locally deposited, corner, wetting-liquid profile establishes the initial conditions for Eq. (1). In addition, wetting-liquid streams through the pore corners driven by the applied liquid-phase pressure gradient. As we shall discover, this weeping flow plays an important role in the snap-off process. Provided that enough liquid is available in the given pore geometry, snap-off may ensue in Fig. 1 (c). Note in Fig. 1 (c,d) that a foam lamella is not produced directly. Rather, a lens forms that subsequently thins to a lamella after emergence from the pore throat and/or after capillary equilibration with the surrounding porous medium.

Unfortunately, the local deposited configuration of corner-liquid due to lens or lamella flow in constricted, cornered pores has not been solved. Nevertheless, Hirasaki and Lawson [22] model and experimentally verify lamellae flow resistance in straight circular tubes flows via a modification of the work of Bretherton [23]. To the first order (i.e. the static case), the curvature of the interface lining pore walls ahead of and behind a translating lamella is identical to the curvature of the lamella Plateau border. However, this case is never reached unless the lamella velocity is identically 0. For a translating lens or lamella, the radius of curvature behind the lamella is smaller compared to that in front of the lens or lamella (refer to Eq. (12) of [22]). The general trends from the analysis of Hirasaki and Lawson are that the difference in curvature between the front and rear of a flowing lamella increases as the static curvature of the lamella Plateau border increases and as the lamella velocity increases. These trends are unambiguous for the case of rigid interfaces and result because flow resistance increases as the static capillary pressure increases. The important conclusion drawn is that a moving lamella does not deposit liquid in pore corners at precisely the equilibrium capillary pressure of the porous medium or the entry curvature of a single gas–liquid interface. Rather, the curvature and capillary pressure at the rear of a translating lamellae are greater than equilibrium and this effect is more pronounced the drier is the medium. Accordingly, a translating lens or lamella perturbs the gas–liquid interfacial curvature establishing the conditions necessary for wetting-liquid accumulation at a pore throat and snap-off of an additional lens.

To quantify the corner-liquid deposition amounts, we adopt a semi-empirical approach. Consonant with smoothly constricted pores and lamella movement rearranging liquid held in pore corners, we assume that the initial amount of liquid throughout the length of a pore is a function of the local cross-sectional size [20]. The minimum curvature at any axial position during lens/lamella flow is the entry curvature of a single gas–liquid interface. To account for the lamella entry process, the initial liquid distribution is obtained by multiplying the minimum curvature profile, as obtained from the single-interface entry curvature at any point, by a factor greater than unity. Thus, a gradient in interfacial curvature is established consistent with lamella movement [22]. Our previous work considered liquid deposited in pore corners throughout the length of the pore at the local value of the single-interface entry curvature, although pore boundaries could be at curvatures different from the entry value [1]. This new condition describes drier pores at elevated capillary pressures.

Once liquid is deposited in the pore corners at a curvature different from that of the porous-medium capillary pressure, it is important to resolve the rate of liquid movement along pore corners relative to the velocity of the lamella or lens that has perturbed the corner interface. This question is answered and discussed in our earlier work [1]. Upon comparing Figs. 11 and 13 of that paper, we find that the dimensionless time (on a common basis) for lens or lamella movement is about an order of magnitude less than for liquid movement through the pore corners. A lamella or lens vacates a pore faster than liquid can flow into the pore as a result of the gradient in interfacial curvature. Thus, corner-liquid profiles laid down by a translating lamella or lens persist for a relatively long period of time and equilibration of corner-liquid with the porous medium is a relatively slow process.

To complete the snap-off analysis, boundary conditions are needed for Eq. (1) at the pore ends. Both constant-curvature and no-curvature-driven-flux boundary conditions are imposed on the pore. A no-curvature-driven-flux boundary condition at both pore boundaries restricts a pore, in a set of serially connected pores, to rearrange only the initial volume of liquid within one pore-length. For simplicity, we refer to this condition simply as a “no-flux” condition. It is apparent that a no-flux condition is quite conservative. Conversely, a “constant curvature” condition connects a pore body to a large source of wetting-liquid. In reality, this is akin to connecting the resistive flow within a corner to a much less resistive supply of liquid. For instance, a gas- and liquid-occupied pore might be connected through pore corners to an adjacent pore, or set of pores, fully filled with water. In the calculations to follow, liquid is supplied to pore boundaries without changing the curvature at the boundaries.

3. Results

Consider first calculations where $\mathrm{Ca_m}$ is set to 0. Here, all rearrangement of liquid occurs strictly because of differences in interfacial curvature. Figs. 2 and 3 display the results from typical calculations for accumulation time, t_a, versus the pore-constriction ratio, λ_c. Times refer to the total elapsed time required to accumulate sufficient liquid to reach an unstable inscribed circle configuration of the interfacial curvature. Once this configuration is reached anywhere along the length of the pore, rearrangement to a pore-spanning lens ensues. Fig. 2 applies to constant-curvature boundary conditions, whereas Fig. 3 applies to no-flux conditions. The ratio P_c/P_{cm} refers to the initial interfacial curvature profile relative to the minimum curvature profile of the pore. Recall that the minimum curvature refers to the local value for entry of a single gas–liquid interface. For example, a ratio of 1.6 sets the capillary pressure at a pore throat to 60% above the single-interface entry capillary pressure of that particular pore. Such a pore contains substantially less wetting-liquid than it did when gas first entered it.

A few comments are in order. The effect of increased capillary pressure is more dramatic in pores with a no-flux boundary condition. This is because such pores only rearrange liquid from within themselves. Liquid is not allowed to flow into the pore from outside the pore boundaries, so the pores are somewhat starved for wetting-liquid. Consequently, these calculations yield a quite conservative evaluation of snap-off given the interconnected nature of porous media. As the capillary pressure increases relative to the single-interface entry pressure, snap-off is only possible

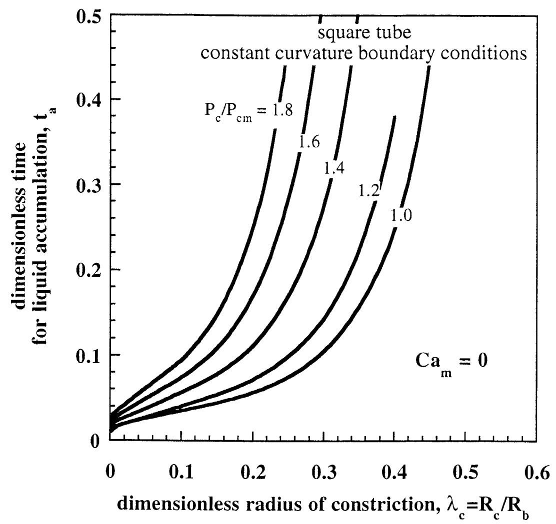

Fig. 2. Dimensionless time for liquid accumulation into a pore throat to cause snap-off for varying constriction ratios. No liquid-phase pressure gradient is imposed ($Ca_m = 0$), and constant-curvature boundary conditions are employed.

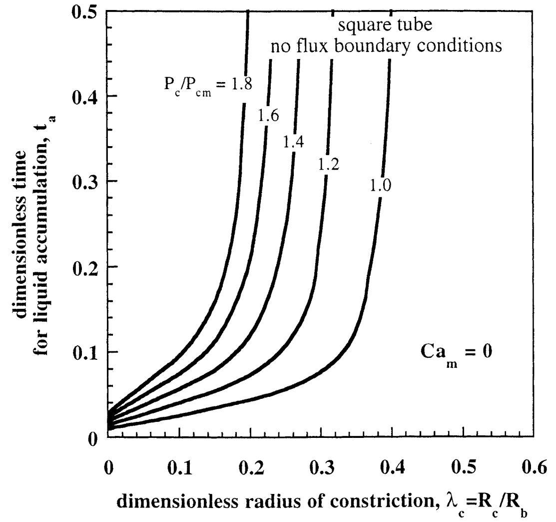

Fig. 3. Dimensionless time for liquid accumulation into a pore throat to cause snap-off for varying constriction ratios. No liquid-phase pressure gradient is imposed ($Ca_m = 0$), and no-flux boundary conditions are employed.

in pores that are increasingly constricted. Note in Fig. 2 that for constant-curvature boundary conditions and P_c/P_{cm} equal to 1.6, snap-off is possible only in pores with dimensionless radii of constriction less than about 0.33. Typical constriction-to-body ratios range from 0.1 to 0.2 in porous sandstones [24] indicating that snap-off should be possible even at these elevated capillary pressures. For smooth but infinitely tight constrictions (i.e. $\lambda_c = 0$), the snap-off position is slightly downstream of the pore neck and moves slightly farther downstream as P_c/P_{cm} increases. Hence, the accumulation time for an infinitely tight constriction always remains non-zero. These results indicate that the assumption of instantaneous capillary-pressure equilibrium via flow along pore corners is never obtained in practice, as is assumed elsewhere [17].

Next, consider snap-off aided by a net liquid-phase axial pressure gradient. The magnitude of the pressure gradient is set through the parameter Ca_m. The effect of a pressure gradient within the wetting-liquid phase is dramatic for relatively wet and relatively dry pores alike. Figs. 4 and 5 examine the role of pressure gradient on snap-off in relatively dry pores for constant-curvature and no-flux boundary conditions, respectively. For illustrative purposes, P_c/P_{cm} is fixed at 1.4 in both figures. Initial conditions are as described above. Interestingly, as Ca_m increases from 0, 10, and 50 to 100, the time for accumulation decreases significantly. Note especially the difference between results at Ca_m equal to 10 and 50. At the larger values of Ca_m, accumulation time is small for virtually all values of λ_c and then asymptotes sharply. The asymptote arises from geometrical considerations and liquid-volume constraints [1]. These modified capillary numbers correspond to liquid pressure drops of 0, 800, 4000, and 8000 kPa m^{-1} (0, 35.4, 177, and 354 psi ft^{-1}), respectively, for a pore with a pore body radius of 100 μm, a length L/R_b of 10, and an interfacial tension of 32 mN m^{-1}. Note that the dimensional pressure gradient is inversely proportional to L/R_b: the gradient is half as large if L/R_b increases by a factor of 2. Pressure gradients for Ca_m equal to 10, 50, and larger are indeed representative of strong foam flow in sandstones at steady state [13,14].

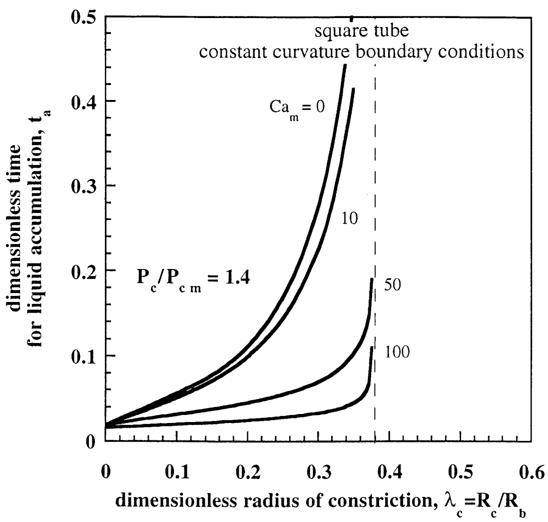

Fig. 4. Dimensionless time for liquid accumulation into a pore throat to cause snap-off for varying constriction ratios. The effect of liquid-phase pressure gradient is illustrated for $P_c/P_{cm} = 1.4$. Constant-curvature boundary conditions are employed.

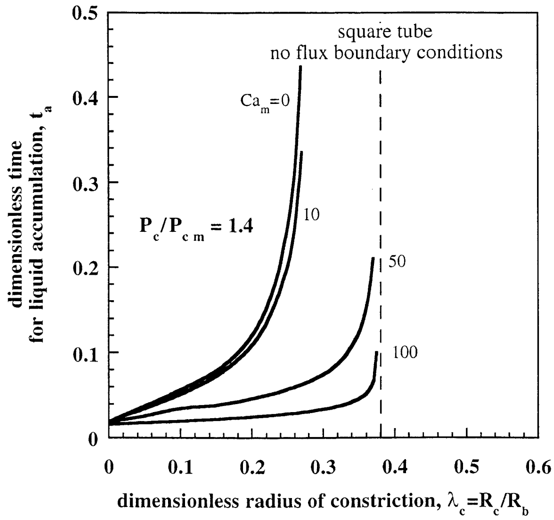

Fig. 5. Dimensionless time for liquid accumulation into a pore throat to cause snap-off for varying constriction ratios. The effect of liquid-phase pressure gradient is illustrated for $P_c/P_{cm} = 1.4$. No-flux boundary conditions are employed.

4. Discussion

The results presented here shed new light on the mechanisms by which foam germination sites remain active or become inactivated. Namely, as opposed to Rossen [17], our calculations show that steady foam generation can occur in porous media by snap-off even when pores contain foam lamellae and are relatively dry. Requirements for snap-off in dry media include elevated foam pressure gradients and constricted pores. The foam-generation process is highly dynamic and, as such, cannot be analyzed sufficiently if one assumes instantaneous capillary equilibrium between the liquid in germination pores and that in the surrounding medium.

We also find that for very dry pores and Ca_m equal to 0 that generation ceases, in agreement with experiment. Chambers and Radke observed the cessation of snap-off at a pore throat in a transparent glass micromodel as the liquid content of the downstream pore body became small (cf. Fig. 20 of [12]). Low liquid content was achieved by injecting only gas into the micromodel so as to dry it out. As Figs. 2 and 3 above illustrate, a curvature driving force alone can become insufficient to cause liquid accumulation and snap-off at capillary pressures about twice the single-interface entry capillary pressure of a pore. On the other hand, Figs. 4 and 5 show that liquid is pumped through pore corners rapidly when the liquid-phase pressure gradient is large. This flowing corner-liquid may accumulate quickly to an unstable configuration at pore throats whenever the pore geometry is sufficiently constricted. The new calculations here confirm the assertion of Chambers and Radke [12] that the Roof geometric criterion [10] is a necessary but not sufficient condition for snap-off.

Our snap-off analysis specifically considers pores in isolation. It is, therefore, beneficial to examine briefly the question of snap-off from a porous-medium-network perspective. As foam is generated, the gas saturation increases as does the porous-medium capillary pressure. With an increase in P_c, progressively smaller pores are entered by gas. Because of the large number of pore throats and bodies within a porous medium, there is practically a continuous distribution of pore sizes, even for a homogeneous porous medium. During multiphase gas and wetting-liquid flow, a fraction of pores remain near or slightly above their capillary entry pressure. Repeated snap-off is most likely in this fraction of pores. Within this same fraction of pores, the capillary pressure fluctuates as foam is intermittently mobilized and trapped [13]. These fluctuations are realized at the pore level as perturbations in the gas–liquid interfacial curvature. Consequently, the calculations summarized in Figs. 2–5 also quantify liquid accumulation for this case.

Recently, Tanzil et al. [25] confirmed the beadpack results of Ransohoff and Radke [5] that a macroscopic low-to-high permeability transition aids foam generation by snap-off. Essentially, the high permeability region must be at least four times more permeable than that upstream. This is in agreement with the Roof geometric criterion [10] that the body-to-throat size aspect ratio must at least be 2. Tanzil et al. [25] also find that snap-off is retarded at high gas fractional flow, even in heterogeneous porous media. This point is in agreement with our calculations above because the wetting-liquid content within pores decreases as the gas fractional flow increases. Thus, snap-off frequency decreases. In many regards, the work of Tanzil et al. [25] is complementary to the conceptual picture of snap-off developed here and in our earlier work [1]. These authors explain the prevalence of bubble germination sites as arising from heterogeneity where ample wetting-liquid is available for repeated snap-off. Our work is in agreement and also explains the experimentally observed effects of gas and liquid velocity on foam bubble size [26] and the measured pressure drops [1,13,14].

The permeability-contrast model of Tanzil et al. [25], while relevant to heterogeneous reservoirs, does not explain the low foam mobility measured in homogeneous sands and sandstones [13,14] and the evolution of bubble size as gas velocity is varied [26]. For instance, Fig. 6 displays the porosity characteristics of a Boise sandstone core measured in our laboratory using gamma-ray densitometry. Note the relatively small variation in porosity about the average of 0.255 with maxima and minima at roughly 0.28 and 0.23, respectively. Considering that permeability correlates with porosity through the Carman–Kozeny relationship [27], the small porosity variations in Fig. 6 do not appear sufficient to meet the minimum 1:4 change in permeability demanded by the permeability-contrast foam-germination

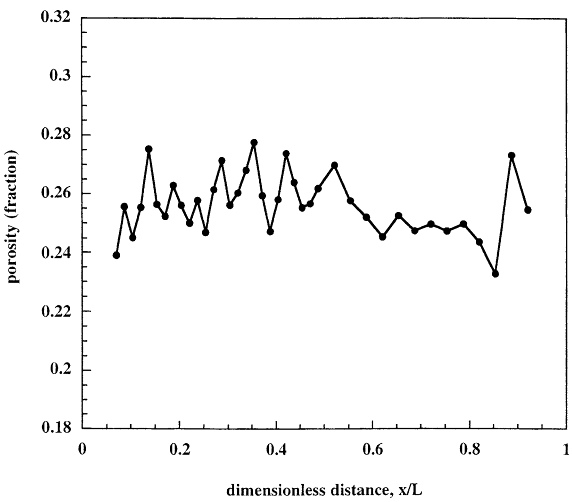

Fig. 6. Porosity profile of a homogeneous Boise sandstone core with average permeability equal to 1.3 μm^2.

model of Tanzil et al. [25]. Nevertheless, strong foam is generated in this core prior to gas breakthrough under a large variety of injection conditions [14] in agreement with our pore level, homogeneous-medium, foam-germination model.

Finally, comments are warranted regarding recent experiments on gas-bubble snap-off in standard glass laboratory pipettes to mimic doubly constricted pores [17]. Clearly, glass pipettes lack the pore corners that permit the rearrangement and accumulation of liquid water at pore throats subsequent to snap-off. The original work of Roof [10] incorporated a groove filed into the wall of a circular cross-section constriction to reflect the important role of nooks and crannies in porous media. Further, the dimensions of a laboratory pipette are large (ca. 10 mm) causing liquid and gas to segregate by gravity forces. Visual inspection of the vertical distribution of the dense wetting-liquid in Fig. 6 (b–d) of [17] shows that nearly all of the liquid resides in the lower half of the pipette. Further, the pipette is inclined at 4–5° from the horizontal. In all views, the gas–liquid interface in the axial direction is horizontal. If capillarity were significant, this interface would have the same angle of inclination as the pipette. In the experiments of [17], capillary forces do not dominate the arrangement of fluid. Bubbles cease to be generated because wetting-liquid is drained from the upstream pore constriction under the influence of gravity. There are neither pore corners nor a liquid-phase pressure gradient sufficient to carry wetting-liquid to the constriction. The doubly constricted nature of the pipette plays no role in this phenomenon. An inclined, singly constricted, circular tube also does not generate lenses. Hence, we conclude that the glass-laboratory-pipette experiments of [17] are not relevant to snap-off in porous media.

5. Summary

In summary, the cornered, constricted pore calculations presented here indicate that repeated snap-off indeed can be responsible for steady foam generation in homogeneous porous media even when the porous-medium capillary pressure is larger than the single-interface capillary entry pressure of a particular set of pores. Calculations including the role of wetting-liquid content are in agreement with previous observations in micromodels of foam generation and cessation of snap-off [12]. Low aqueous-phase saturation and correspondingly high capillary pressure within a pore, or set of pores, does not categorically preclude steady foam generation by snap-off. Factors that contribute to repeated snap-off include smoothly constricted pores with smal throats, as expressed by the ratio $\lambda_c = R_c/R_b$, elevated pressure gradients in the liquid phase, and lamella or lens movement that establishes gradients in the axial profile of interfacial curvature. These elements all appear to be present in natural porous media undergoing strong foam flow.

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